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# Lagrangian-Relaxation-Based Self-Repairing Mechanism for Wi-Fi Networks

**MING-CHI TSAI[1], (Student Member, IEEE), FRANK YEONG-SUNG LIN[1], AND YEAN-FU WEN[2], (Member, IEEE)**
[1]Department of Information Management, National Taiwan University, Taipei 10617, Taiwan
[2]Institute of Management Information Systems, National Taipei University, Taipei 23741, Taiwan

Corresponding author: Yean-Fu Wen (yeanfu@mail.ntpu.edu.tw)

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**ABSTRACT** Wi-Fi was developed to support software-defined networks that are crucial for achieving high quality of service for next generation wireless networks. In this software-defined networking technology, network resources are utilized to reduce the effects of several influential factors such as the limited number of nonoverlapping channels, co-channel interference, rapidly changing distribution of customers, and access point (AP) failure. These factors cause irregular network traffic and service unavailability in some users. In this paper, we address the problems causing the AP failure and interference. The studied problems were modeled as linear and nonlinear mathematical programming problems. The Lagrangian relaxation approach, which is a type of divide-and-conquer method, was used to solve the load distribution problems near optimally. A self-repairing heuristic multiple-level load-balancing traffic adjustment was proposed to manage the problems pertaining to the AP failure. The delay difference metric, which is defined as the difference between tolerable delay and transmission delay, was used to evaluate the difference between the upper bound and lower bound of the delay. Moreover, the metric was used to estimate the improvement ratio between the existing methods and the proposed method. Modifiable transmission power ranges (which involve the cell breathing method) and association managements are adjusted to minimize the narrow gap and improve the self-repairing performance. Thus, resources are appropriately allocated to users, and adequate QoS is attained.

**INDEX TERMS** Delay difference, Lagrangian relaxation, load balancing, self-organizing network, Wi-Fi.

## I. INTRODUCTION

The high quality of service (QoS) for next generation wireless networks is crucial. However, to address the high QoS requirements, methods must be developed to ensure network reliability and availability. In this paper, we aim to adjust network mechanisms to avoid network service interruption due to AP failure. An automatic repair mechanism is required to solve the network disconnection problem. A self-repairing function, which is executed with software-defined networks (SDNs) [1], [2], is adopted for Wi-Fi networks. The function employs a self-configuration mechanism to adjust network parameters, such as signal strength, channel allocation, signal-to-interference-plus-noise ratio (SINR), and handover threshold, to repair network failure, to recover interrupted networks, and to avoid network service interruption [3].

Software-defined network (SDN) is a type of network framework, which allows network administrator to re-build network structure without modifying hardware equipment or to dynamically configuring the network devices by software implementation methods [3]. The next generation wireless networks (including Wi-Fi) support SDN with self-repairing function, a novel technique to ensure reliability, and a new set of networks to achieve high quality of service (QoS). The characteristics of SDN are essential to our network model since the re-construction and the recursive adaption of the network are supported for the proposed method to dynamically configure the connection.

When an AP encounters critical interference or when it is out of service, users cannot access the network. In this case, a mobile device (MD) attempts to connect to the other available APs on the basis of the current signal strength it receives. A novel technique is proposed for SDNs that uses a controller to ensure high performance within a given service area [4]. The primary idea of association management is to use SDNs to yield a new set of networks to continuously serve MDs in a failed AP. Thus, We propose a new algorithm compared with three existing methods to overcome the problems related to finding a new set of network to serve MDs in a failed AP.

The network capacity of a service area reduces when one or more APs are out of service. The traffic load in a service area that has a broken AP increases because of the service capacity reduction. The MDs that belong to a particular failure AP can individually select another AP to avoid the transfer of traffic load only to a few APs. This concept of load balancing is introduced to enhance the performance of a service area.

This paper utilizes the SDN to achieve the self-repairing function with few modifications of the network [3]. It is not necessary to change topology, protocol, the available channels, bandwidth, access points, and modulation. What we can do is to adjust the power range, to re-associate the AP-MD link, and to integrate the system data. The networks structure is less changed and the modification of the self-repairing function is few.

Most studies on QoS consider delay jitter [5], [6], minimum delays [7] or delay jitters as the comparison metrics [8]. However, those metrics of estimating the QoS might not be suitable for various types of MDs. The traffic requirements, delays, and delay jitters may vary because the MDs have diverse processing powers and network interface specifications.

Quality of experience (QoE) is used to evaluate the QoS on the basis of the user perspective, and it differs from conventional network side performance evaluation [9]. Not all applications require the same level of QoS and the same extent of delay minimization. Thus, QoE is used to reflect the actual requirements for the self-organization in wireless networks in this paper. The delay range required to reserve the resources for the MDs is determined on the basis of neighboring wireless resources.

Some self-repairing algorithms, such as equal power allocation with fixed healing channels (EPA–FHC) [10] and cooperation resource allocation (CRA) [11], with self-repairing channels are designed for cellular networks [12]. However, when a network is considered to have the self-repairing function, it means that the normal APs need to support the failed APs, which causes system throughput degradation. After the normal APs support the failed APs, the problem of fairness arises. To solve these problems, some algorithms are proposed, such as fairness-aware cooperation resource allocation (FA-CRA) [2], Co-operative beamforming-based resource allocation (CoBRA) [13], and collaborative self-repairing with opportunistic indoor base-station selection (OIS) [14]. These algorithms precisely describe the self-repairing problem and address partial of the problems that remain fairness problem unresolved. Table 1 shows some representative works and makes comparison of their characteristics.

**TABLE 1. Self-Healing Methods comparisons.**

| | |
|---|---|
| Having self-repairing function with severe degradation | CRA |
| | EPA–FHC |
| To improve fairness and maximize system throughput. | FA-CRA [2] |
| | Emphasize fairness, and adopt logarithm to enhance transmission fairness. |
| | CoBRA [13] |
| | Use new antenna techniques and maximize the beamforming gain to improve throughput and fairness simultaneously. |
| | OIS [14] |
| | Use constraints to improve the fairness. |

In this paper, the Lagrangian relaxation (LR) method [15] is used to address the self-healing problem. By using the LR method, the gap between the proposed solution and the optimal solution pertaining to the lower bound (LB) is obtained through the Lagrange dual problem by the mathematical derivation. The LR method not only compares the performance of the existing methods for solving problems related to AP failure with that of the novel algorithm but also identifies the distance of the optimal solution from the derived solution. In other words, this paper provides a foundation for evaluating the self-repairing issues concerned with APs, illustrates the ceiling of probability issue with the proposed model, and shows the restrictions of improvement degree.

This paper proposes a modified self-repairing algorithm with the load balance effect that is utilized from our previously proposed water ripple algorithm (WRA) [16] and employs the LR method to evaluate the quality of the solution by estimating the gap between the upper bound (UB) and LB. Conventional measurement standards, such as system capacity or throughput, cannot reflect the actual experience of users of various types of Wi-Fi network. Thus, we adopt the delay of network as the measurement standard. This paper also investigates the load on the APs on the basis of the load balance effect, and it explores user requirements rather than consider the uniform resource distribution to achieve the fairness of a system. By considering the actual experience and different users' demands, the true fairness is achieved instead of formal equality. The transmission delay must be lower than the tolerable delay for each MD to maintain QoE, in particular, for interactive services. Hence, the different tolerable delay was specified for each application, such as multimedia with the lower tolerable delay and web service with the relatively larger tolerable delay. The delay difference is set as the objective function to maximize the minimum delay difference to achieve the weighted fairness. The weight is based on the length of the tolerable delay. This paper proposes a multiple-level load-balancing traffic adjustment (MLTA) algorithm to solve the self-healing problem. A short tolerable delay indicates that data must be transmitted in short waiting and transmission time.

The objectives of this paper are described as follows:

1) Modeling the self-repairing problem with linear and nonlinear integer programming and solving the problem by using an optimization-based approach.
2) Proposing the LR-based algorithm to reduce the gap between the UB and LB of the objective function values that are the delay differences and obtaining a high improvement ratio between the existing methods and the proposed method.
3) Presenting experimental cases to reveal the improvements of the proposed MLTA algorithm.

The remainder of this paper is organized as follows. In Section II, the literature review is summarized, and the methods of various studies are compared. In Section III, the network model and mathematical formulation are presented. The solution approach is presented in Section IV. In Section V, the proposed approach is evaluated, and the related discussion is presented. Finally, the conclusion is presented in Section VI.

## II. RELATED LITERATURE

A feature of the Wi-Fi campus network and wireless metropolitan mesh network is that an AP involved in both these networks possesses the same service set identifier to provide appropriate connection to the MDs moving around a given service area [17]. MDs associate with APs on the basis of the association management so that the connections can be adjusted on the basis of the current network status. Association management, which is a non-distributed mechanism, can be conducted by using the mechanism of 5G wireless communication networks [18], [19]. Next generation wireless networks will utilize a centralized mechanism that is provided by a cloud radio access network (C-RAN) to manage the resources of a network [20]. The backend network in a C-RAN dynamically assigns a remote radio head (RRH) [21] to provide wireless services.

In this paper, we discuss the maximization of minimum transmission delay differences, which are evaluated using quantitative methods through fairness measure models, and evaluate the appropriate conditions and fairness issues for obtaining a balanced network by using delay metrics, while other studies utilize throughput and transmission latency [7]. There are many measures by which the load on a network can be estimated; some other measurements are Jain's fairness index (FI) [22], standard deviation (SD), and log function.

Although most scholars use Jain's FI to evaluate the level of balance in load distribution, the difference between SD and log function reflected by the index is small when the values already have some kind of balance degree. Moreover, traffic distribution affects the FI value. Thus, the SD is utilized to obtain a clear distribution of the load values. The log function can also be used in the objective function instead of the max–min mathematical programming method because it is feasible to use the log function. However, because the SD and log are not normalized within a fixed range, the extent of differences is not useful for diverse value ranges. In this paper, we use LR as the primary research method [15]; thus, we use max–min mathematical programming method instead of the log function. The primary evaluation metric in this paper to estimate the performance of the proposed solution is the max–min delay difference.

There are several relative recent studies of the self-healing topic, and the differences and relations between them and our work are summarized in Table 2. Asghar, Farooq and Imran had surveyed self-heating solutions in the mobile cellular networks. They provide taxonomy of the existing literature on self-healing [23]. Palacios *et al.* [24] had studied self-healing framework to manage a high-dimensional next-generation wireless networks. The network reconfiguration and fault isolation are studied for a self-healing distribution network [25]. This work concentrates on Wi-Fi network and proposes a near-optimal max-min delay difference solution.

A decentralized algorithm, known as maximizing local throughput (MLT) [26], is designed to select APs. This algorithm focuses on related parameters, such as throughput. In [27], delay is used as an evaluation metric, and probe delay (PD) and mean probe delay (MPD) algorithms are proposed for evaluation. The primary related parameter in [28] is distance, and the distance between an AP and user devices was transformed into moveable steps. In another study, a game approach is adopted, and the Nash equilibrium is considered to predict user behavior [29]. Another intuitive algorithm for AP selection is presented in [30]. This study directly estimates Internet access capability as an evaluation metric. From the user viewpoint, Pang et al. proposed an algorithm to allow users to select an appropriate AP based on a report produced by users [31]. In [32], the system selected an AP with the highest received signal strength indicator and the lowest interference. This method combines two algorithms to implement the shortest-distance-first and the maximum-bit-rate-first approaches. The shortest distance neighboring AP (SDNA) algorithm is employed for the shortest-distance-first approach, and the maximum bit-rate neighboring AP (MBNA) algorithm is employed for the maximum-bit-rate-first approach. The AP selection mechanism should consider environmental interference to avoid poor network performance. Thus, Kim *et al.* [33] mainly concentrated on interference problems. By contrast, we used delay and network association mechanisms with the shortest distance first, maximum bit rate, and minimum delay to solve the load distribution problem.

## III. NETWORK MODEL AND PROBLEM DESCRIPTION

### A. NETWORK MODEL

The service area selected in this paper is divided into several wireless service areas that are covered by a set of APs, namely $V_{AP}$ (Figure 1). Each wireless area is covered by several APs such that an MD $v$ that belongs to $V_{MD}$ has multiple candidate APs for association. The power range of an AP can be dynamically adjusted to avoid interference and to execute

**TABLE 2.** Recent literature comparisons.

| Citation | Factor | Difference and relevant |
|---|---|---|
| [1], [2], [3], [4], [24] | Software-defined network (SDN) | The SDN concepts illustrated in [1], [2], [3], [4], [24] are referred in this work. A technique is proposed for SDNs that uses a controller to ensure high performance from the service area viewpoint [4]. SDN is used to support self-repairing functions, a novel technique to ensure reliability, and a set of networks to achieve high quality of service (QoS). |
| [9] | Quality of experience (QoE) | Quality of experience (QoE) is used to evaluate the QoS on the basis of the user perspective, and it differs from conventional network performance evaluation [9]. QoE is used to reflect the actual requirements for the self-organization in wireless networks in this paper. |
| [2], [10], [11] [12], [13], [14] | Self-repairing algorithms | Some self-repairing algorithms, such as Equal power allocation with fixed healing channels (EPA–FHC) [10] and cooperation resource allocation (CRA) [11], with self-repairing channels are designed for cellular networks [12]. Furthermore, fairness-aware cooperation resource allocation (FA-CRA) [2], co-operative beamforming-based resource allocation (CoBRA) [13], and collaborative self-repairing with opportunistic indoor base-station selection (OIS) [14] addressed partial self-repairing problems that remain fairness problem unresolved. This work concentrates on self-healing with fairness issue. |
| [23], [24], [25] | Self-healing solutions for various type of network | Asghar, Farooq and Imran had surveyed self-healing solutions to reduce cost and to improve reliability for mobile cellular network [23]. Palacios et al. had studied self-healing framework to manage a high-dimensional wireless networks [24]. The network reconfiguration and fault isolation are studied for a self-healing distribution network [25]. This work concentrates on Wi-Fi network and proposes a near-optimal max-min delay difference solution. |
| [26], [34] | AP selection | A decentralized algorithm, known as maximizing local throughput (MLT) [26], is designed to select APs. The behaviour of wireless sensor networks is unstable due to node's failure or low battery. The concepts of dynamically building-up clusters [34] are similar to the method of this work to find out the available AP. They found an energy-efficient policy to opt cluster head, but we found a low delay differential for both self-healing solution and quality-of-experience. |
| [27], [28], [29], [30], [31], [32] | AP selection Metrics | In [27], delay is used as an evaluation metric, and probe delay (PD) and mean probe delay (MPD) algorithms are proposed for evaluation. The primary related parameter in [28] is distance, and the distance between an AP and user devices was transformed into moveable steps. A game approach is adopted, and the Nash equilibrium is considered to predict user behaviour [29]. Another intuitive algorithm for AP selection is presented in [30]. Pang et al. propose an algorithm to allow users to select an appropriate AP based on a report produced by users [31]. In [32], the system selects an AP with the highest received signal strength indicator and the lowest interference. This study directly estimates Internet access capability as an evaluation metric. |
| [35] | Self-management | Baccarelli et al. had studied Internet of Everything networks, which is a type of self-managing and self-orchestrating eco-systems, to achieve energy-efficiency [35]. Although the type of network differs from our work, the main technological challenges self-management, self-organization, reduced communication latency, wise usage of the network bandwidth, and resource limitation are addressed in this work. |

the self-repairing function. An MD associates with another AP by using a SDN. Each AP utilizes diverse spectral ranges to reduce co-channel interference (CCI). Assume that an MD

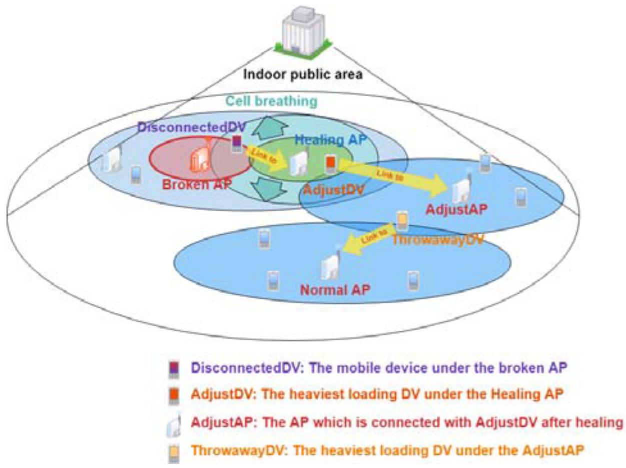


**FIGURE 1.** System model of the SON-based MLTA algorithm.

$v$ that belongs to $V_{MD}$ is associated with only one AP. The various applications that are executed on an MD have diverse traffic requirements and QoE.

## B. CHANNEL ASSIGNMENT

Owing to using 5GHz, there are much more available channels and higher transmission rates. However, even such more available channels in 5GHz, CCI might occur among diverse Wi-Fi protocols, as presented in Figure 2 [36]. The spectral bands used for various Wi-Fi protocols are limited to the same spectral range. One 40-MHz channel (i.e., Channel 38) using IEEE 802.11n covers two 20-MHz channels (i.e., Channels 36 and 40) using 802.11a. Table 3 illustrates the overlapping situation of frequency bands with different channels.

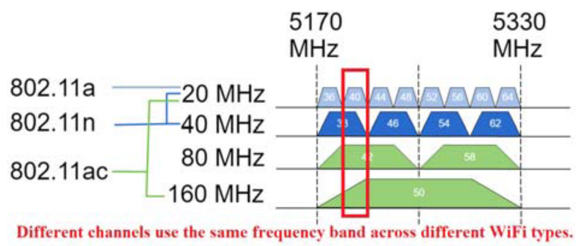


**FIGURE 2.** Distribution of the bands at 5 GHz.

**TABLE 3.** Channels under the same frequency bands.

| Frequency | | 5170-5250 MHz | | | |
|---|---|---|---|---|---|
| Type | Bandwidth | Channel ID | | | |
| 802.11a | 20-MHz | 36 | 40 | 44 | 48 |
| 802.11n | 40-MHz | 38 | | 46 | |
| 802.11ac | 80-MHz | 42 | | | |
| 802.11ac | 160-MHz | 50 | | | |

We consider atomic spectral band with a minimum bandwidth range of 20-MHz. All selected channels for a protocol standard are transformed into atomic spectral bands for co-channel evaluation. A channel assigned in a service area will not be assigned within the interference range as far as possible to reduce the CCI and transmission delay.

This paper considers channel assignment to decrease CCI such that the adjacent APs are assigned with diverse channels [37]. However, this paper sets no explicit restrictions of neighboring APs being assigned with unique channels. If the same channel is assigned to adjacent APs, CCI might cause higher interference and decrease network performance. Considering objective function, there will be a trend to make the adjacent APs assigned with diverse channels.

### C. TOLERABLE DELAY MODEL

The media access control (MAC) protocol, which listens before transmission, is used to avoid signal collision to reduce interference. Serious retransmission problems may not occur when using the MAC protocol if MD–AP transmission pairs operate under the same frequency band, which implies the use of overlapping channels [38]. However, if one or more MD–AP pairs use the same channel, a long time is required during data transmission for signal detection by the MAC to avoid collision. When the MAC mechanism is used, the long-term waiting time is the summation of the data transmission time for different MD–AP transmission pairs within the interference range.

**TABLE 4. Tolerable delay for various applications.**

| Tolerable delay | Application type | Example |
|---|---|---|
| Extremely low | Instant video or picture transmission | Facetime |
| Low | High stream flow | Youtube |
| Middle | Quick response and middle flow | Network game |
| High | Low flow and not instant | E-mail, Web surfing |

The tolerable delay differs on the basis of the application. Table 4 presents the diverse tolerable delays for various applications. A transmission flow with a short tolerable delay requires a short transmission delay to satisfy system restriction and user demand. Conversely, flows with longer tolerable delays can handle longer transmission delays because the user service demands corresponding to those flows are not so urgent. From the viewpoint of resource allocation, a larger bandwidth is required for large amounts of resources to obtain a shorter delay. Thus, the tolerable delay is set and the resource allocation is conducted such that the QoS is enhanced and user requirements are satisfied.

### D. PROBLEM DESCRIPTION

For self-repairing, the tolerable delay and the resource allocation problems are specified in a mathematical format and are modeled by using linear and nonlinear mathematical planning problems. The assumptions during modeling are as follows:

1) A wireless network is well deployed to cater to a service area that includes at least two APs with adaptive power ranges.
2) If a deployed AP is switched off, one or more APs can be assigned to the network in a short range.
3) MDs in a system are considered to be stationary in a very-short and continuous time slot.
4) There are $N$ nonoverlapping independent channels.

The range of delay is the time used for transmitting processing that users must really endure; eventually we utilize delay as the main metrics to evaluate the results to reflect the user experience. The bandwidth metric has enclosed in delay evaluation because the delay values are derived from traffic requirements and bandwidth. The higher bandwidth results in shorter delay. To estimate the service quality and the fairness among the served MDs, the objective function is designed to maximize the minimal delay difference, which is defined as the tolerable delay minus the transmission delay, as presented in (1).

$$\max \min_{v \in V_{MD}} (T_v - d_v) \tag{1}$$

Subject to the following constraints:

#### 1) CHANNEL ASSIGNMENT

Consider $\alpha_u$ as a binary decision variable to determine whether an AP is switched on or not. When $\alpha_u = 1$, the AP $u$ is switched on, and when $\alpha_u = 0$, the AP $u$ is switched off. The variable $n_{hu}$ is a binary decision variable. When AP $u$ is assigned a channel $h$, $n_{hu} = 1$; otherwise, $n_{hu} = 0$. On the basis of (2), the AP $u$ must be assigned one channel when it is switched on.

$$\alpha_u \leq \sum_{h \in H} n_{hu}, \quad \forall u \in V_{AP} \tag{2}$$

The constraint in (3) indicates that an AP is assigned with only one channel.

$$\sum_{h \in H} n_{hu} \leq \alpha_u, \quad \forall u \in V_{AP} \tag{3}$$

#### 2) SINR THRESHOLD

The variable $\kappa_{th}$ denotes the signal threshold, which is a requirement for gaining access. The decision variable $\eta_{uv}$ is used to indicate whether the MD $v$ is in the service area of the AP $u$. On the basis of (4), the decision variable $\eta_{uv}$ of the affected neighboring MDs is equal to zero when the SINR value $\beta_{uv}$ of a neighboring node is less than the threshold value. Otherwise, variable $\eta_{uv}$ can be set to be equal to 1 to indicate that the AP $u$ experiences interference from MD $v$, as presented in (5).

$$\frac{\beta_{uv}}{\kappa_{th}} \geq \eta_{uv}, \quad \forall u \in V_{AP},\ v \in V_{MD} \tag{4}$$

$$\frac{\beta_{uv} - \kappa_{th}}{M_1} \leq \eta_{uv}, \quad \forall u \in V_{AP},\ v \in V_{MD} \tag{5}$$

#### 3) CELL BREATHING

Note that $p_u$ represents the transmission power range of the AP $u$ in the service area and is limited within the range $(p_{min}, p_{max})$. On the basis of (6), the power range of the AP

$u$ is larger than the minimum power range $p_{min}$ when the AP $u$ is switched on. However, the maximum power range $p_{max}$ is limited by (7), which is limited by the functional ability [7], [39], [40]. Therefore, the decision variable $p_u$ has a restricted range, as presented in (8).

$$\alpha_u p_{\min} \leq p_u \tag{6}$$
$$p_u \leq \alpha_u p_{\max} \tag{7}$$
$$0 \leq p_u \leq p_{\max} \tag{8}$$

#### 4) ASSOCIATION MANAGEMENT

The binary decision variable $\delta_{uv}$ is equal to one when MD $v$ is associated with an AP $u$; otherwise, $\delta_{uv} = 0$. The decision variable $\eta_{uv}$ is used to indicate whether MD $v$ is in the service area of AP $u$ or not by using (4) and (5). If the device $v$ is associated with the AP $u$, then $\delta_{uv}$ and $\eta_{uv}$ are estimated to be equal to 1 by using (9). Otherwise, $\eta_{uv}$ and $\delta_{uv}$ are equal to 0, which implies that the MD $v$ is not in the service area of AP $u$. One device can be associated with only one AP. Moreover, on the basis of (10), the total number of APs associated with an MD $v$ should not be higher than 1.

$$\delta_{uv} \leq \eta_{uv}, \quad \forall u \in V_{AP},\ v \in V_{MD} \tag{9}$$
$$\sum_{u \in V_{AP}} \delta_{uv} \leq 1, \quad \forall v \in V_{MD} \tag{10}$$

Once an MD $v$ is associated with an AP $u$, the AP $u$ must be switched on. The decision variable $\alpha_u$ is set to one on the basis of (11) to indicate the switched on state. By contrast, MD $v$ cannot connect to AP $u$ when the AP $u$ is switched off. If no MD $v$ is connected to AP $u$, then the AP $u$ must be switched off on the basis of (12).

$$\delta_{uv} \leq \alpha_{uv}, \quad \forall u \in V_{AP},\ v \in V_{MD} \tag{11}$$
$$\alpha_u \leq \sum_{v \in V_{MD}} \delta_{uv}, \quad \forall u \in V_{AP} \tag{12}$$

#### 5) CAPACITY

$\beta_{uv}$ is the SINR value, which is estimated using the signal range between an AP $u$ and an MD $v$. The capacity, which is denoted as $c_v$, was calculated by mapping it to the SINR value list. A considerable number of available channels is presented in the entire system. The system bandwidth should be larger than the aggregated user requirements; otherwise, some user transmissions are interrupted. The SINR function that is denoted by the right-hand side of (13) calculates the SINR value on the basis of the power of an AP $u$ and the power of a neighboring interfering AP $u'$ under the assumption that signal fading and the square of distance are in inverse proportion. The APs are pre-deployed in fixed positions. Several methods, such as GPS, i-Beacon, the received power signal strength from APs, triangulation, etc., support to locate the MDs. The topology is given so we assume at that moment the positions of APs and MDs are given. The variable $\beta_{uv}$ represents the SINR value that is calculated from the powers of AP $u$ and AP $u'$. The SINR $\beta_{uv}$ is simultaneously influenced by the interference from a neighboring AP $u'$ and the square of distance.

$$\beta_{uv} = SINR(p_u, dis_{uv}, p_{u'}, dis_{u'v'}) = \frac{p_u/(dis_{uv})^2}{\sum_{u' \in V_{AP}} p_{u'}/(dis_{u'v'})^2},$$
$$\forall v \in V_{MD},\quad u \in V_{AP},\ u' \in V_{AP},\quad v' \in V_{MD},\quad u \neq u',\ v \neq v' \tag{13}$$

To obtain the actual delay, the capacity must be calculated from the SINR value that is influenced by the power range and the distance. The function $f(\beta_{uv})$ is a stepped function that maps the SINR value to the capacity, as presented in Subsection III.B. The dBm range for each step can be obtained using the modulation and coding scheme (MCS) equation in [41], after which data rate can be obtained using an equation presented in [42]. The capacity $c_v$, which is a positive value, is used to calculate the available bandwidth of the MD $v$ that is associated with a serving AP, as presented in (14). The capacity should not be less than zero, as presented in (15).

$$c_v = f(\beta_{uv}), \quad \forall v \in V_{MD},\ u \in V_{AP} \tag{14}$$
$$0 \leq c_v, \quad \forall v \in V_{MD} \tag{15}$$

#### 6) DELAY

The delay is defined as a combination of the transmission time and the queuing time, where $\omega$ reflects the queuing time and includes the ready to send (*RTS*), clear to send (*CTS*), short inter-frame spacing (*SIFS*), and coordination function inter-frame space (*DIFS*). Equation (16) is used to calculate the node-to-node delay between an MD $v$ and an AP $u$ when MD $v$ transmits data. Here, $\gamma_v$ represents the data traffic requirements of MD $v$. $N_1$ and $N_2$ are large enough to repair the connection as required. To limit the values of $N_1$ and $N_2$ within a reasonable range, the delay variable $d_{uv}$ should not be less than 0 and, similarly to the other delay variables, should not be larger than the tolerable delay, as presented in (17).

$$\left(\frac{\gamma_v}{c_v} + \omega\right) - (1 - \delta_{uv}) N_1 \leq d_{uv}, \quad \forall v \in V_{MD},\ u \in V_{AP} \tag{16}$$
$$0 \leq d_{uv} \leq T_v, \quad \forall v \in V_{MD}, \forall u \in V_{AP} \tag{17}$$

Here, $d_v$ denotes the delay of the MD $v$. Each MD can transmit its data to the MDs that use the same channel and are within the signal detection area. As the media is shared, the transmission delay of an MD $v$ is the summation of the transmission delays that are observed while transmitting data to all these MDs, as presented in the left-hand side of (18). The delay variable $d_v$ should not be equal to 0. Moreover, to limit the value within a reasonable range a propagation time $t_v$ exists even if the channel that the MD intended to transmit data on contains no MDs, as presented in (19).

$$\sum_{k \in V_{MD}} d_{uk} - (1 - \delta_{uv}) N_2 \leq d_v, \quad \forall u \in V_{AP},\ v \in V_{MD} \tag{18}$$
$$t_v \leq d_v \leq T_v, \quad \forall u \in V_{AP},\ v \in V_{MD} \tag{19}$$

## IV. SOLUTION METHODOLOGY

The LR-based approach is used to propose heuristics, which obtains near-optimal solution. The approach provides a series of procedures to solve the primal and Lagrange dual problems. A set of Lagrange multipliers is used to analyze the influence of decision variables and selection metrics. By using the LR approach, we obtain two updated important result values, UB (upper bound) and LB (lower bound) corresponding to the results value of the primal problem and the Lagrange dual problem respectively per iteration. A set of Lagrange multipliers was used to analyses the influence of decision variables and evaluation metrics. Once all the subproblems generated by relaxing the constraints are optimally solved, the LR method guarantees that the optimal solution must be in the range between UB and LB. It is known how far the proposed solution is from the optimal solution within the LR gap. Accordingly, there are two sets of value differences in this work. One is $UB$, which denotes as delay difference. Another is the LR gap, which is calculated through the equation $|UB-LB|/|UB|$. The Lagrange dual solution provides the LB to demonstrate the efficiency of the proposed solution. Furthermore, existing methods, such as the SDNA, MBNA, and minimum delay neighboring AP (MDNA), are modified to compare with the proposed method.

### A. LR SOLUTION

In general, the LR-based approach is used to solve the minimization problem. We reformulate the objective function (1) as (IP) by involving the additional constraint presented in (20). The objective function (IP) is a minimization problem, which is subject to constraints (2)–(20).

$$\min d \tag{IP}$$
$$s.t.\ d_v - T_v \leq d \tag{20}$$

Equations (2)–(7), (9), (11)–(14), (16), and (18) are relaxed to the objective function (IP) with a set of multipliers such that the problem can be separated by using the divide-and-conquer method to optimally solve the Lagrange dual problem (LR). After relaxation, we add some natural constraints presented in (21). The equation (21) is a delay constraint that it keeps the bound of decision variable $d$ in the range (0,min($T_v$)). Delay is impossible to be negative. Hence, the delay should not exceed the maximum tolerable delay to satisfy the user requirement. However, our original objective function, namely the maximized minimal problem, is not a standard format for LR method so that the objective function (1) is reformulated as (IP) by involving the additional constraint presented in (20). Accordingly, the original problem is transformed into the minimization problem. The direction of the sign in (IP) is reversed. Consequently, equation (21) is derived.

Equation (21) restricts the decision variable within a reasonable range. By using the LR method, we can relax the constraints by moving the decision variables to the same side of the equation, and multiplying a Lagrangian multiplier, and then adding to the objective function. In this paper, we relax 14 constraints so there are 14 Lagrangian multipliers. The number of relaxed constraints is not fixed. It is determined the mathematical model and whether the subproblems can be optimally solved. The strategic used in this study tries to separate the decision variables to ensure no NP-Complete subproblems (e.g., backpack problem, bipartite matching problem) in dual problem.

$$\min \left[\begin{aligned} & d + \sum_{v\in V_{MD}} \mu_v^1 (d_v - T_v - d) \\ & + \sum_{u\in V_{AP}} \mu_u^2 \left(\alpha_u - \sum_{h\in H} n_{hu}\right) \\ & + \sum_{u\in V_{AP}} \mu_u^{14} \left(\sum_{h\in H} n_{hu} - \alpha_u\right) \\ & + \sum_{u\in V_{AP}} \sum_{v\in V_{MD}} \mu_{uv}^9 \left(\frac{\beta_{uv} - \kappa_{th}}{M_1} - \eta_{uv}\right) \\ & + \sum_{u\in V_{AP}} \sum_{v\in V_{MD}} \mu_{uv}^{10} \left(\eta_{uv} - \frac{\beta_{uv}}{\kappa_{th}}\right) \\ & + \sum_{u\in V_{AP}} \mu_u^3 (\alpha_u p_{\min} - p_u) \\ & + \sum_{u\in V_{AP}} \mu_u^4 (p_u - \alpha_u p_{\max}) \\ & + \sum_{u\in V_{AP}} \sum_{v\in V_{MD}} \mu_{uv}^5 (\delta_{uv} - \eta_{uv}) \\ & + \sum_{u\in V_{AP}} \sum_{v\in V_{MD}} \mu_{uv}^{11} (\delta_{uv} - \alpha_u) \\ & + \sum_{u\in V_{AP}} \mu_u^{12} \left(\alpha_u - \sum_{v\in V_{MD}} \delta_{uv}\right) \\ & + \sum_{u\in V_{AP}} \sum_{v\in V_{MD}} \mu_{uv}^{13} (\beta_{uv} - SINR(p_u, dis_{uv}, p_{u'}, dis_{u'v'})) \\ & + \sum_{u\in V_{AP}} \sum_{v\in V_{MD}} \mu_{uv}^6 (c_v - f(\beta_{uv})) \\ & + \sum_{u\in V_{AP}} \sum_{v\in V_{MD}} \mu_{uv}^7 \left(\left(\frac{\gamma_v}{c_v} + \omega\right) - (1-\delta_{uv}) N_2 - d_v\right) \\ & + \sum_{u\in V_{AP}} \sum_{v\in V_{MD}} \mu_{uv}^8 \left(\sum_{k\in V_{MD}} d_{uk} - (1-\delta_{uv}) N_2 - d_v\right) + \end{aligned}\right] \tag{LR}$$

On the basis of the LR solution, all the multipliers are nonnegative. $Z_D(\mu_1, \mu_2, \mu_3, \mu_4, \mu_5, \mu_6, \mu_7, \mu_8, \mu_9, \mu_{10}, \mu_{11}, \mu_{12}, \mu_{13}, \mu_{14})$ is the Lagrange dual problem of (IP). The dual problem (D) is divided into ten subproblems; the solution to each subproblem is presented in Appendix A. Each subproblem is solved using an optimal algorithm, and the summation of the objective values of all the subproblems is the result for the dual problem (D). The subgradient method is used to solve problem (D) that was transformed into the LR problem to maximize the dual problem which is subject to a set of multipliers. The update rule for the Lagrangian dual problem (D) is the subgradient method which updates the set of multipliers per iteration.

The update rule for the Lagrangian dual problem (D) is solved by the subgradient method which updates the sets of multiplier per iteration. In each iteration $i$, we update $\mu = \mu_1, \mu_2, \mu_3, \mu_4, \mu_5, \mu_6, \mu_7, \mu_8, \mu_9, \mu_{10}, \mu_{11}, \mu_{12}, \mu_{13}, \mu_{14})$ by $\mu^{i+1} = \mu^i + t^i k^i$, where $k$ is a vector of the subgradient of $Z_D(\mu_1, \mu_2, \mu_3, \mu_4, \mu_5, \mu_6, \mu_7, \mu_8, \mu_9, \mu_{10}, \mu_{11}, \mu_{12}, \mu_{13}, \mu_{14})$, and $t^i$ is the step size. Note that $t^i$ is calculated as $t^i = \lambda(Z_{IP} - Z_D)/\left|k^i\right|^2$, where $\lambda$ is a value between 0 and 2. Initially, $\lambda = 2$, and it is divided by 2 when the UB does not improve even after configured number of iterations. The objective value (LB) of the Lagrange dual problem is updated when the obtain result is larger the current LB. The $Z_{IP}$ is the optimal UB value after iteration $i$. We attempt to maximize the objective value of (D) to reduce the gap between the UB and the LB. The optimization value will be in the area to show the gap between the Lagrange dual results (namely, LB) and the primal results (namely, UB).

Note that the LR problem is subject to (8), (10), (15), (17), (19), and (21).

$$\min_{v} (T_v) \leq d \leq 0 \tag{21}$$

$$\begin{aligned} &\textit{Objective function}: Z_D = \max Z_D\,(\mu_1, \mu_2, \mu_3, \mu_4, \mu_5, \mu_6, \\ &\qquad\qquad \mu_7, \mu_8, \mu_9, \mu_{10}, \mu_{11}, \mu_{12}, \mu_{13}, \mu_{14}) \\ &\textit{subject to}\ \mu_1, \mu_2, \mu_3, \mu_4, \mu_5, \mu_6, \mu_7, \mu_8, \mu_9, \\ &\qquad \mu_{10}, \mu_{11}, \mu_{12}, \mu_{13}, \mu_{14} \geq 0 \end{aligned} \tag{D}$$

### B. OBTAINING A PRIMAL FEASIBLE SOLUTION

The primary idea of the proposed feasible solution is to reassign the MDs that were served by a failed AP to the neighboring APs by using a subset of multipliers. Then, the traffic load should be adjusted among the APs to maximize the minimum delay difference. The MDs are reassigned to the APs on the basis of the shortest-distance-AP-first approach when the APs are initialized. The proposed algorithm is termed as multiple-level load-balancing traffic adjustment (MLTA) algorithm. This implies that association management is used to adjust the connections when an AP fails in an area. This heuristic attempts to adjust the traffic load by reassigning MDs to the APs that are outside the service area through SDN techniques. The coordinated multi-point (CoMP) technology is also used to support the proposed algorithm.

The pseudocode is presented in Algorithm 1. Regardless of the optimal solution, we update the UB on the basis of the primal feasible solution that has the optimal objective value after iteration $i$. Algorithm 2 presents the primal feasible solution of the proposed LR-based method to obtain the UB values.

### C. COMPARED ALGORITHMS

With a dynamic power range, two existing cell breathing solutions are used for self-repairing [40]. This paper adjusts

**Algorithm 1** MLTA

```
while user M is under the broken AP do
  for each candidate AP N of MD M do
    mark the AP n according to decision variable δ_uv
    if an AP n is found then
      re-associate MD M to AP n
      adjust the power range
flag = true
R = ∞
while flag is true do
  results = getDelayGap(); // Get delay gap of each device
  if results is not small than R then
    flag = false
  else
    R = results
  for each candidate AP U of MD adjustDVdo
    skip broken AP and adjustAP
    mark the AP u with the smallest delay gap
    if an AP u is found then
      re-associate MD adjustDVto AP u
      adjust the power range of AP u
      update adjustAP's connection MD list and power range
    else
      MD adjustDVstill associate to AP adjustAP
      flag2 = true
      for all MD v do
        remark v as unmarked
    while flag2 is true do
      for each connection MD V of AP adjustAP do
        mark the throwawayDV with the largest delay gap
        unmark throwawayDV, which is not adjustDV and throwawayDV
      if an MD throwawayDV is found then
        mark throwawayDV's original AP as M3
        for each candidate AP K of MD throwawayDV do
          skip broken AP and adjustAP
          mark the AP k with the smallest delay gap
          if an AP k is found then
            re-associate MD throwawayDV to AP k
            adjust the power range of AP k
            update AP connection list and power range
            flag2 = false
          else
            MD throwawayDVstill associate to AP M3
            Mark throwawayDV as remarked
      else
        flag2 = false
```

**Algorithm 2** LR

InitializeEnvironment(); // initialize experiment environment;
*UB* = the compared algorithms' result such as SDNA() or MBNA()or MDNA();
*LB* = -1000; //small enough;
*scalar* = 2.0; //for step size.
*osc_ctr* = 0; //oscillation counter.
*cvg_ctr* = 0; //oscillation counter.
*iteration* = 0;
**While** *cvg_ctr* < *LR_CVG_DEGREE* **and** *LB* < *UB* **and** *iteration* < *MAX_LR_ITERATION***do**
  $LU = \sum_{i=1}^{10} subproblem\,(i)$
  **if** *LB* is better than *Tightest_LB* **then**
    *Tightest_LB* = *LB*;
    *osc_ctr* = 0;
  **else**
    *osc_ctr* = osc_ctr + 1;
    **if** *osc_ctr* > LR_OSC_DEGREE **then**
      *scalar* = *scalar* / 2;
      *osc_ctr* = 0;
      *cvg_ctr*=*cvg_ctr* + 1;
    **end if**
  **end if**
  *UB* = MLTA(); //getting primal feasible solution;
  update_multiplier(scalar, iteration); //update multiplier;
  iteration = iteration + 1;
**end while**

the power range by using a recursive concept that is similar to the water ripple concept [16]. The adjustment is initiated from the failed AP and is conducted until the APs on the outer ring are adjusted. Then, many association metrics are used for reassigning the MDs that belong to failed APs to the nearby APs that are available. Moreover, attempts are made to reassociate the MDs with a minimum delay difference with the APs on the outer ring of the present service area.

#### 1) SDNA

The main idea of this method is to reassign an MD that belongs to a failed AP to the neighboring AP that is at the shortest distance. The pseudocode is presented in Algorithm 3; however, the minimum delay is revised to that of the nearest AP. This method is considerably intuitive and quite common. When an AP fails, the system makes the closest AP be used to support the failed AP.

#### 2) MAXIMUM BIT RATE NEIGHBORING AP (MBNA)

The main idea of this method is similar to MDNA. The two methods differ on the basis of the fact that in the MBNA method, the minimum delay is replaced with the maximum bit rate. This method is slightly efficient because it uses the bit rate to evaluate the system performance while determining the AP that is an optimal substitute for the failed AP.

**Algorithm 3** MDNA

**while** all MDs associated to the broken AP is unmark **do**
  find an unmark MD *v* with the maximum traffic requirement
**for** each candidate AP *u* of MD *v* **do**
  skip the broken AP
  mark the AP *m* with the maximum delay
  associate MD *v* to AP *m*
  **If** the power range is shorter than the required range to cover MD *v* **then**
    extend the power range
Output the delay difference

#### 3) MINIMUM DELAY NEIGHBORING AP (MDNA)

The main idea of MDNA is to associate the MD, of which the original AP is broken, to the neighboring AP with the minimum delay, as presented in Algorithm 3. The method utilizes delay to evaluate the system performance while determining the AP that is an optimal substitute for the failed AP.

The time complexities of the important algorithms are summarized in Table 5. The worst case is considered for each method. The highest time complexity is the Lagrange dual solution. The number of iteration $|T|$ might be large to observe convergence results. The time complexities of compared methods are the same with $O(|MD||AP|)$. Actually, the number of $|MD|$ might be small under served by an AP. The number of candidate APs is limited within maximum signal range.

**TABLE 5.** Time complexity comparison among the evaluation methods.

| Method | Time complexity | Description |
|---|---|---|
| MLTA | $O(\|R\|\|AP\|\|MD\|^2)$ | Suppose the number of while-loop (Line 9) is $\|R\|$ to converge. The execution time for re-association (Line 15) is $\|AP\|\|MD\|$. The time complexity of AP connection list $\|MD\|$. |
| LR-Dual (LB) | $O(\|T\|\|AP\|\|MD\|^2)$ | Suppose the number of Lagrange dual iteration is $\|T\|$. The highest time complexity of LR dual problem is determined by (Sub10) with $O(\|AP\|\|MD\|^2)$. |
| MBNA | $O(\|MD\|\|AP\|)$ | The amount of required adjustment of $\|MD\|$ and $\|AP\|$ might be small. The worst case for the MBNA is $O(\|MD\|\|AP\|)$. |
| MDNA | $O(\|MD\|\|AP\|)$ | The time complexity of this method is similar to MBNA with the worst case $O(\|MD\|\|AP\|)$. |
| SDNA | $O(\|MD\|\|AP\|)$ | The number of required adjustment nodes is the number of MDs associated to the neighbouring APs. |

## V. EVALUATION AND DISCUSSION

### A. EXPERIMENTAL ENVIRONMENTS

Wi-Fi networks, AP distribution, and MD wireless network access scenarios were analyzed using experiments.

**TABLE 6. Summary of cases with different settings.**

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| Number of MDs | 150-250 | Number of APs | 40 |
| The type of APs | 802.a/g/n/ac | Tolerable delay | 53.64-71.82 ms |
| Traffic load | 0.7-5.0 Mbps | Wi-Fi bit rates | 6-693 Mbps* |
| Spectral ranges | 2.4 and 5GHz | Maximum signal range | 30-70 m |

*Note: Bit rates are set on the basis of the Wi-Fi standard and transmission range, which reflects the level of the signal.

Five experimental cases were designed to evaluate the performance of the proposed heuristic. The network was initialized as described in Subsection III.A; $|V_{AP}|$ APs and $|V_{MD}|$ MDs were arranged in a service area measuring $100 \times 100$ m$^2$. This area was selected because of the highly dense characteristics of the 5G network and the computing capacity of the equipment used in the experiment. Each MD was initially associated with various types of Wi-Fi APs (namely, IEEE 802.11a/g/n/ac) with various transmission ranges and bit rates. Table 6 lists the attributes of the experimental environment. The experiments were conducted using a self-developed program that was implemented in C++ and executed on a Windows system.

### B. EXPERIMENTAL CASES

Usually, APs fail due to high load or much more associated MDs. Five cases were designed to evaluate the LR-based self-repairing flexibility heuristics. The higher the delay difference is, the longer the available time for transmission is. The designed cases are as follows:

LR gap (Case 1): The number of iterations (100–1000) is set to analyze the gap between the UB (which is observed from the primal feasible solution) and the LB (which is observed from Lagrange dual solution).

Number of MDs (Case 2): The number of MDs in a given area was changed from 150 to 250 MDs per $100 \times 100$ m$^2$ service area. The traffic load served by an AP was increased to demonstrate the effect of the self-repairing solution.

Multiple levels of traffic load (Case 3): Two control variables—the uniform distribution of MDs and the number of MDs within a specific area—were used to evaluate the concentration of traffic. The traffic load in some areas is higher than that in other areas. Therefore, the unbalanced traffic load distribution due to a failed AP was used to evaluate the traffic distribution mechanism of the self-repairing solution.

Length of the given tolerable delay (Case 4): When MDs have shorter tolerable delays, the urgency of finding another AP with a higher capacity to serve the MDs that belong to a failed AP is higher. By contrast, the MDs with a longer tolerable delay may be reassigned to any other AP that would not affect the objective value.

Variance in traffic load (Case 5): This case is similar to the density of MDs. A high traffic load might be exerted on a specific node, which affects the objective value. The high traffic load cannot be easily distributed among several neighboring APs to enable the other MDs to adjust the AP load and thus increase the difference between the transmission delay and tolerable delay.

### C. EXPERIMENTAL RESULTS

The experimental results of the five cases are presented as follows:

#### 1) LR GAP (CASE 1)

We use the LR-based method to evaluate the gap between the UB and LB that is obtained from the primal feasible solution and Lagrange dual solution. The UB value is obtained from the minimum results derived from the proposed LR-based heuristic and related methods. The LB value is obtained from the Lagrange dual solution. Then, the gap is calculated using the formula $|UB - LB|/|UB|$, where the absolute value is also used to obtain the positive values because the LR transformation (IP) generates negative values. The proposed heuristic MLTA provides an approximate solution that is based on the multiplier to obtain a near-optimal solution. Figure 3 presents the experimental results for the UB and LB values obtained per iteration. The gap between the proposed solution and the Lagrange dual problems converges within 60 iterations. The average and maximum gaps between the UB and LB are 12.65% and 14.96%, respectively. When there is a smaller gap between UB and LB, it is implied that the proposed solution approaches the real optimal solution. We transform the original problem into the minimization problem, so we reformulate the objective function, which is

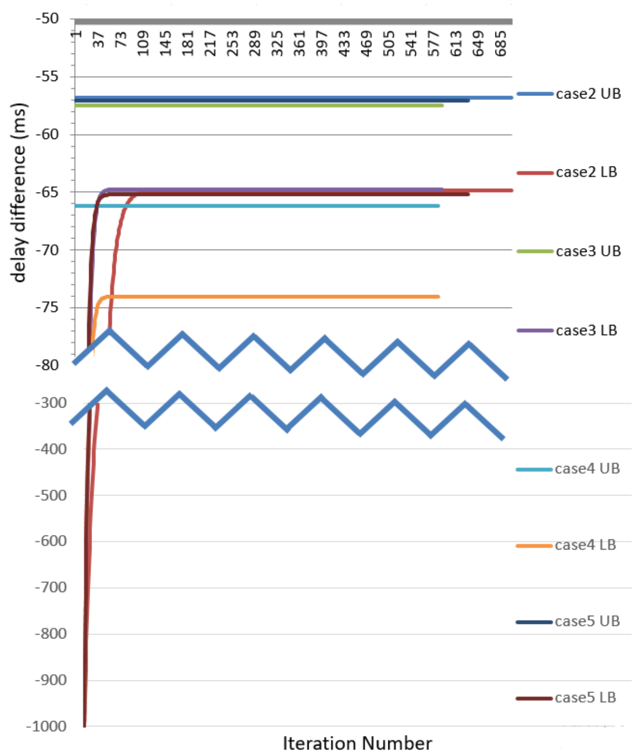


**FIGURE 3. Experimental UB and LB obtained per iteration for the designed cases.**

turned into minimizing the negative delay difference from maximizing the minimum delay difference to fit in the LR approach concept. This is the reason why the evaluated delay difference in Fig. 1 is negative.

#### 2) NUMBER OF MDS (CASE 2)

Figure 4 presents the experimental results of Case 2. The results reveal that a higher number of MDs cause a larger traffic load. A lower delay difference is observed when a higher traffic load is exerted on a fixed number of APs. The improvement ratio is calculated using the following formula: *Improvement ratio* $= |OtherMethod - MLTA|/|OtherMethod|$, where the absolute value is also used to obtain the positive values because the LR transformation (IP) generates negative values. The proposed MLTA method obtained the highest delay difference, which was considered as the optimal performance. The average improvement ratio was 12%.

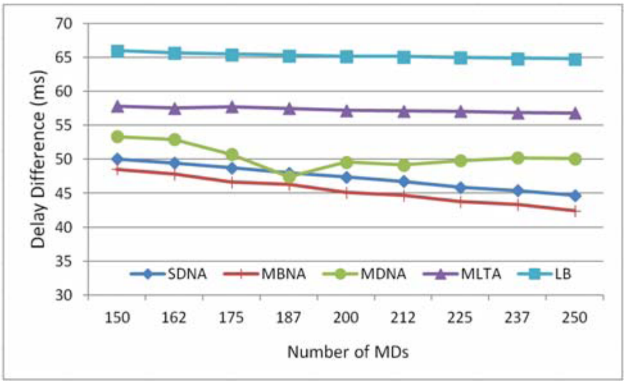


**FIGURE 4.** Delay differential evaluated by increasing the number of MDs.

#### 3) MULTIPLE LEVELS OF TRAFFIC LOAD (CASE 3)

Figure 5 presents the experimental results of Case 3. The results reveal that the variation in the number of MDs within a specific area influences the delay difference obtained using the proposed MLTA method and the other aforementioned methods. The load is distributed among the neighboring APs.

In the MDNA method, when a lower number of MDs are located in a small area, a larger delay difference is observed and approximated to the objective value of the proposed LR-based method. This indicates that the tolerable delay constraint might be violated even when a slight addition in traffic is introduced. However, the improvement ratio was high when many MDs were distributed within the given service area.

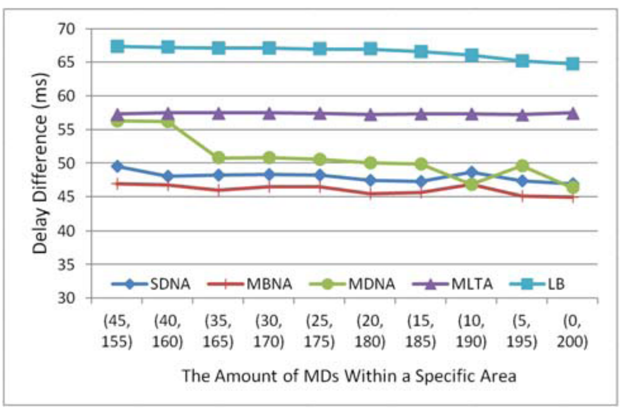


**FIGURE 5.** Delay difference evaluated by increasing the deployed nodes (namely, increasing the number of MDs within a specific area).

#### 4) LENGTH OF THE GIVEN TOLERABLE DELAY (CASE 4)

Figure 6 presents the experimental results of Case 4. The results reveal that a long average tolerable delay causes a long delay difference. The most crucial aspect of this evaluation is to ensure that the proposed MLTA method yields stable results. The delay difference obtained by using the proposed method was approximately 5.24 ms higher than those obtained by using the other methods. Thus, the delay difference is not affected by the average tolerable delay.

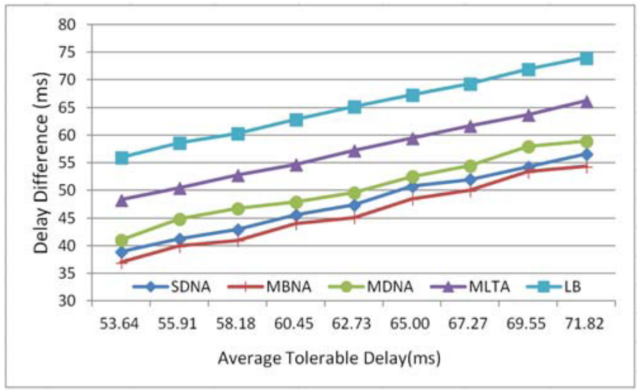


**FIGURE 6.** Delay difference evaluated by increasing the average tolerable delay.

#### 5) VARIANCE IN TRAFFIC LOAD (CASE 5)

Figure 7 presents the experimental results of Case 5. The results reveal that when a high traffic load is exerted by each MD, a small delay difference is obtained. The delay difference was small because of the high traffic load; however, the decrease in the amplitude in the proposed MLTA method was lower than those in the other methods. The amplitude obtained by using the proposed method was approximately 11% higher than those obtained by using the other methods. This result might be due to the following: (1) the MLTA method assigns the MDs with high traffic to the APs that have a light load, (2) the traffic load is balanced by using the delay to satisfy the QoE, and (3) the traffic is distributed to the APs on the outer ring of the service area.

### D. DISCUSSION

The node (MDs and APs) deployment density is a crucial factor for estimating the performance of the proposed heuristics. A high density results in a large tolerable delay range;

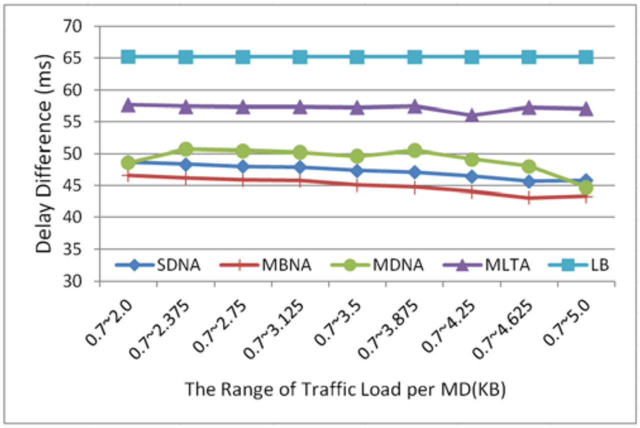


**FIGURE 7.** **Delay difference evaluated by increasing the traffic load per MD.**

this implies that the method has a high performance. The results of Case 2 reveal that the MLTA algorithm performed much better than other algorithms if the number of MDs is sufficiently high. Analyzing the experimental data indicated that all the improvement rates were higher than 11%, except those with fewer than 175 MDs. The results of Case 2 also demonstrate that MLTA always had a stable performance, even when the other algorithms exhibit poor performance.

The results of Case 3 indicate that the performance of the MLTA algorithm surpasses those of the other algorithms. However, if the density of the topology is too low, the performance of the MDNA algorithm is strong; thus, the improvement rates between the MLTA algorithm and the compared algorithms are not very high. However, despite these lowered rates, the MLTA algorithm still outperforms the other algorithms.

When designing Case 4, a problem appears concerning the tolerable delay. The value of tolerable delay could not be very small because a very small tolerable delay cannot satisfy user demands. Thus, the system is unable to find an optimal solution.

The results of Case 5 suggest that traffic load had a slight effect on the objective value. When modifying the parameters to demonstrate the effect of traffic load, the effect on the objective value is difficult to reflect, even if we double the traffic load or centralize the traffic load. However, the traffic load was inversely related to the objective values. Because the MLTA algorithm has a load-balancing effect, it is difficult to affect the objective values due to traffic load.

This concept could be used both for the existing networks and the next-generation networks because of the flexibility of the self-organization networks. The self-repairing issues had become important with the automation trend and the development of various environments. The core concept of the self-repairing is to support the failure APs with the healing APs. Furthermore, the problem is modelled as linear and non-linear mathematical program with a general graph. Thus, the self-repairing function could be executed even with diverse techniques. For example, the Wi-Fi technique integrates for the fifth generation (5G) mobile network techniques.

## VI. CONCLUSION

This paper adopts the concept of self-healing to deal with the coverage and the degradation problem. The problem is formulated as linear and nonlinear mathematical programming problems and solved by using the proposed LR-based method. The primary method to obtain the primal feasible solution is to use Lagrange multipliers that are assigned certain weights to identify a near-optimal set of APs for the MDs that belong to the failed APs. The experimental results reveal that the LR's primal feasible solution obtained by using the MLTA algorithm selects the APs with the maximum difference between the evaluated delay and the tolerable delay. The proposed method has an average improvement ratio of 12.3%, compared with the other algorithms. The network density and variation in the traffic load are the two crucial factors that yield the advantages of the proposed algorithm. Moreover, the issue of self-repairing has become important with the automation trend and the development of various environments. The core concept of the self-repairing is to support the failure APs with the healing APs, so the self-repairing function could be executed even with diverse techniques. For example, the function could also be executed with the fifth generation (5G) mobile networks technique, not only with the Wi-Fi technique.

## APPENDIX A
## SUBPROBLEM SOLUTIONS

Subproblem (Sub1) is related to the decision variable $d$.

Objective function

$$Z_{Sub1} = \min\left\{d - \sum_{v\in V_{MD}} \mu_v^1 d\right\} = \min\left\{\left(1 - \sum_{v\in V_{MD}} \mu_v^1\right) d\right\}$$

Subject to (21). (Sub1)

If $1-\sum_{v\in V_{MD}}\mu_v^1$ is positive, the minimum value of $d$ should be selected to minimize the subproblem. The solution of the subproblem is $\left(1-\sum_{v\in V_{MD}}\mu_v^1\right)\min_v(-T_v)$. Conversely, if $1-\sum_{v\in V_{MD}}\mu_v^1$ is negative, then $d$ must be 0 to minimize the subproblem. Then, the solution of the subproblem is 0.

Subproblem (Sub2) is related to the decision variable $d_v$.

Objective function

$$\begin{aligned} Z_{Sub2} &= \min\left(\sum_{v\in V_{MD}} \mu_v^1 d_v - \sum_{u\in V_{AP}}\sum_{v\in V_{MD}} \mu_{uv}^8 d_v - \sum_{v\in V_{MD}} \mu_v^1 T_v\right) \\ &= \min\left\{\sum_{v\in V_{MD}}\left[\left(\mu_v^1 - \sum_{u\in V_{AP}} \mu_{uv}^8\right) d_v - \mu_v^1 T_v\right]\right\} \end{aligned}$$

Subject to (19). (Sub2)

This subproblem is similar to (Sub1). Even in the ideal situation, the delay cannot be equal to zero. That is, the difference between actual delay and the tolerable delay cannot be $T_v$. The minimum value of the delay must be $c_v$. If $\mu_v^1 - \sum_{u\in V_{AP}} \mu_{uv}^8$ is positive, $d_v$ must be $c_v$ to minimize the subproblem. The solution of the subproblem is $\sum_{v\in V_{MD}} \left[\left(\mu_v^1 - \sum_{u\in V_{AP}} \mu_{uv}^8\right) c_v - \mu_v^1 T_v\right]$. If $\mu_v^1 - \sum_{u\in V_{AP}} \mu_{uv}^8$ is negative, $d_v$ must be equal to $d_v$ to minimize the subproblem. The solution of the subproblem is $\sum_{v\in V_{MD}} \left[\left(\mu_v^1 - \sum_{u\in V_{AP}} \mu_{uv}^8\right) T_v - \mu_v^1 T_v\right]$.

Subproblem (Sub3) is related to the decision variable $n_{hu}$.

Objective function

$$Z_{Sub3} = \min\left(\sum_{u\in V_{AP}} \mu_u^2 \sum_{h\in H} n_{hu} + \sum_{u\in V_{AP}} \mu_u^{14} \sum_{h\in H} n_{hu}\right)$$

$$= \min\left(\sum_{u\in V_{AP}} \left(\mu_u^2 + \mu_u^{14}\right) \sum_{h\in H} n_{hu}\right)$$

Subject to $n_{hu}$ being binary. (Sub3)

Because $n_{hu}$ is binary, the solution of the subproblem is 0 in the extreme situation when all $n_{hu}$ are 0. However, this situation is unrealistic, because it implies that APs select no channels. That is, all APs are switched off. The subproblem can be solved through the aforementioned process.

Subproblem (Sub4) is related to the decision variable $\alpha_u$.

Objective function

$Z_{Sub4}$

$$= \min\left(\begin{array}{l} \sum_{u\in V_{AP}} \mu_u^2\alpha_u - \sum_{u\in V_{AP}} \mu_u^{14}\alpha_u + \sum_{u\in V_{AP}} \mu_u^3\alpha_u p_{\min} \\ - \sum_{u\in V_{AP}} \mu_u^4\alpha_u p_{\max} - \sum_{u\in V_{AP}} \sum_{v\in V_{MD}} \mu_{uv}^{11}\alpha_u \\ + \sum_{u\in V_{AP}} \mu_u^{12}\alpha_u \end{array}\right)$$

$$= \min\left[\sum_{u\in V_{AP}} \left(\mu_u^2 - \mu_u^{14} + \mu_u^3 p_{\min} - \mu_u^4 p_{\max} + \mu_{uv}^{12} - \sum_{v\in V_{MD}} \mu_{uv}^{11}\right)\alpha_u\right]$$

Subject to $\alpha_u$ being binary. (Sub4)

If $\mu_u^2 - \mu_u^{14} + \mu_u^3 p_{\min} - \mu_u^4 p_{\max} + \mu_{uv}^{12} - \sum_{v\in V_{MD}} \mu_{uv}^{11}$ is positive, $\alpha_u$ must be 0 to minimize the subproblem. If $\mu_u^2 - \mu_u^{14} + \mu_u^3 p_{\min} - \mu_u^4 p_{\max} + \mu_{uv}^{12} - \sum_{v\in V_{MD}} \mu_{uv}^{11}$ is negative, $\alpha_u$ must be 1 to obtain the minimum objective value of the subproblem.

Subproblem (Sub5) is related to the decision variable $\delta_{uv}$.

Objective function

$Z_{Sub5}$

$$= \min\left(\begin{array}{l} \sum_{u\in V_{AP}} \sum_{v\in V_{MD}} \mu_{uv}^5\delta_{uv} + \sum_{u\in V_{AP}} \sum_{v\in V_{MD}} \mu_{uv}^{11}\delta_{uv} \\ - \sum_{u\in V_{AP}} \mu_u^{12} \sum_{v\in V_{MD}} \delta_{uv} - \sum_{u\in V_{AP}} \sum_{v\in V_{MD}} \mu_{uv}^7(1-\delta_{uv})N_1 \\ - \sum_{u\in V_{AP}} \sum_{v\in V_{MD}} \mu_{uv}^8(1-\delta_{uv})N_2 \end{array}\right)$$

$$= \min\left[\sum_{u\in V_{AP}} \sum_{v\in V_{MD}} \left(\begin{array}{l} \left(\mu_{uv}^5 + \mu_{uv}^{11} - \mu_u^{12} + \mu_{uv}^7 N_1 \right. \\ \left. +\mu_{uv}^8 N_2\right)\delta_{uv} - \mu_{uv}^7 N_1 - \mu_{uv}^8 N_2 \end{array}\right)\right]$$

Subject to (10). (Sub5)

To minimize the objective function, we consider the restrictions $\sum_{u\in V_{AP}} \delta_{uv} \leq 1, \forall v \in V_{MD}$. In this situation, the minimum $\left(\mu_{uv}^5 + \mu_{uv}^{11} - \mu_u^{12} + \mu_{uv}^7 N_1 + \mu_{uv}^8 N_2\right)$ must be selected. In these restrictions, $\delta_{uv}$ is equal to 1 and the others variables are equal to 0. Therefore, we select the minimum $\left(\mu_{uv}^5 + \mu_{uv}^{11} - \mu_u^{12} + \mu_{uv}^7 N_1 + \mu_{uv}^8 N_2\right)$ that is multiplied by $\delta_{uv}$. In this case, the value is one. Otherwise, the others cases are multiplied by $\delta_{uv}$, and the value is 0. Finally, we sum the constants to obtain the final result.

Subproblem (Sub6) is related to the decision variable $\beta_{uv}$.

Objective function

$Z_{Sub6}$

$$= \min\left(\begin{array}{l} \sum_{u\in V_{AP}} \sum_{v\in V_{MD}} \mu_{uv}^9 \left(\frac{\beta_{uv} - \kappa_{th}}{M_1}\right) \\ - \sum_{u\in V_{AP}} \sum_{v\in V_{MD}} \mu_{uv}^{10} \left(\frac{\beta_{uv}}{\kappa_{th}}\right) \\ + \sum_{u\in V_{AP}} \sum_{v\in V_{MD}} \mu_{uv}^{13}\beta_{uv} - \sum_{u\in V_{AP}} \sum_{v\in V_{MD}} \mu_{uv}^6 f(\beta_{uv}) \end{array}\right)$$

$$= \min\left[\sum_{u\in V_{AP}} \sum_{v\in V_{MD}} \left(\left(\frac{\mu_{uv}^9}{M_1} - \frac{\mu_{uv}^{19}}{\kappa_{th}} + \mu_{uv}^{13}\right)\beta_{uv} - \frac{\mu_{uv}^9\kappa_{th}}{M_1} - \mu_{uv}^6 f(\beta_{uv})\right)\right]$$

Subject to $\beta_{uv}$ being binary. (Sub6)

Every $\beta_{uv}$ has its own value. Because the APs and device users are stationary for a short time interval, we can utilize the fixed distance and power range to obtain the value of $\beta_{uv}$. Subsequently, the solution to minimize the subproblem can be obtained using the brute-force method.

Subproblem (Sub7) is related to the decision variable $\eta_{uv}$.

Objective function

$$Z_{Sub7} = \min \left[ -\sum_{u\in V_{AP}} \sum_{v\in V_{MD}} \mu_{uv}^{9}\eta_{uv} + \sum_{u\in V_{AP}} \sum_{v\in V_{MD}} \mu_{uv}^{10}\eta_{uv} - \sum_{u\in V_{AP}} \sum_{v\in V_{MD}} \mu_{uv}^{5}\eta_{uv} \right]$$
$$= \min \left( \sum_{u\in V_{AP}} \sum_{v\in V_{MD}} \left( -\mu_{uv}^{9} + \mu_{uv}^{10} - \mu_{uv}^{5} \right) \eta_{uv} \right)$$

Subject to $\eta_{uv}$ being binary. (Sub7)

If $-\mu_{uv}^{9} + \mu_{uv}^{10} - \mu_{uv}^{5}$ is positive, then $\eta_{uv}$ must be 0 to minimize the subproblem. Conversely, if $-\mu_{uv}^{9} + \mu_{uv}^{10} - \mu_{uv}^{5}$ is negative, then $\eta_{uv}$ must be equal to 1 to minimize the subproblem.

Subproblem (Sub8) is related to the decision variable $p_u$.

Objective function

$$Z_{Sub8} = \min \left[ \begin{array}{l} -\sum_{u\in V_{AP}} \mu_{u}^{3} p_u + \sum_{u\in V_{AP}} \mu_{u}^{4} p_u \\ -\sum_{u\in V_{AP}} \sum_{v\in V_{MD}} \mu_{uv}^{13} SINR\left(p_u, dis_{uv}, p_{u'}, dis_{u'v'}\right) \end{array} \right]$$
$$= \min \left[ \sum_{u\in V_{AP}} \left( -\mu_{u}^{3} p_u + \mu_{u}^{4} p_u - \sum_{v\in V_{MD}} \mu_{uv}^{13} SINR\left(p_u, dis_{uv}, p_{u'}, dis_{u'v'}\right) \right) \right]$$

Subject to (8). (Sub8)

To simplify the subproblem, we discretize the $p_u$. We consider the maximum power range, that is, 70 units, for 802.11n and reduce the power range by five units for each adjustable power size. We recalculated the SINR value by using the discrete $p_u$ and simultaneously considered the constants of the $p_u$ to minimize the subproblem. Accordingly, the objective function is modified as

$$Z_{Sub8'} = \min \left[ \sum_{u\in V_{AP}} \left( -\mu_{u}^{3} + \mu_{u}^{4} - \sum_{v\in V_{MD}} \mu_{uv}^{13} \left( \frac{1/(dis_{uv})^2}{\sum_{u'\in V_{AP}} p_{u'}/(dis_{uv})^2} \right) \right) p_u \right]$$

to obtain the solution by minimizing the subproblem, the brute-force method is used to provide a feasible solution due to the finite possible values of $p_u$.

Subproblem (Sub9) is related to the decision variable $c_v$.

Objective function

$$Z_{Sub9} = \min \left( \sum_{u\in V_{AP}} \sum_{v\in V_{MD}} \mu_{uv}^{6} c_v + \sum_{u\in V_{AP}} \sum_{v\in V_{MD}} \mu_{uv}^{7} \left( \frac{\gamma_v}{c_v} + \omega \right) \right)$$
$$= \min \left( \sum_{u\in V_{AP}} \sum_{v\in V_{MD}} \left( \mu_{uv}^{6} c_v + \mu_{uv}^{7} \frac{\gamma_v}{c_v} + \mu_{uv}^{7} \omega \right) \right)$$

Subject to (15). (Sub9)

Because $c_v$ is a stepped function, it has a finite value. Thus, we utilized the brute-force method to optimally solve the subproblem. Because the size of the matrix of possible values of $c_v$ is small, we solve the subproblem in a relatively short time.

Subproblem (Sub10) is related to the decision variable $d_{uv}$.

Objective function

$$Z_{Sub10} = \min \left( -\sum_{u\in V_{AP}} \sum_{v\in V_{MD}} \mu_{uv}^{7} d_{uv} + \sum_{u\in V_{AP}} \sum_{v\in V_{MD}} \mu_{uv}^{8} \sum_{k\in V_{MD}} d_{uk} \right)$$
$$= \min \left( -\sum_{u\in V_{AP}} \sum_{v\in V_{MD}} \mu_{uv}^{7} d_{uv} + \sum_{u\in V_{AP}} \sum_{v\in V_{MD}} d_{uv} \sum_{k\in V_{MD}} \mu_{uk}^{8} \right)$$
$$= \min \left( \sum_{u\in V_{AP}} \sum_{v\in V_{MD}} \left( \sum_{k\in V_{MD}} \mu_{uk}^{8} - \mu_{uv}^{7} \right) d_{uv} \right)$$

Subject to (17). (Sub10)

The summation $\sum_{k\in V_{MD}} d_{uk}$ implies that the delay of devices $k$ under the AP $u$ and is similar to $d_{uv}$. Thus, we combined both variables and reformulated the formula to solve the subproblem. If $\sum_{k\in V_{MD}} \left(\mu_{uk}^{8} - \mu_{uv}^{7}\right)$ is positive, $d_{uv}$ must be equal to 0 to minimize the subproblem. Conversely, if $\mu_{uk}^{8} - \mu_{uv}^{7}$ is negative, $d_{uv}$ must be equal to $T_v$ to minimize the subproblem.

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**MING-CHI TSAI** received the B.S. degree in business administration and the M.S. degree in information management from National Taiwan University, Taipei, Taiwan, in 2014 and 2016, respectively, where he is currently pursuing the Ph.D. degree in information management. His research interests include the development of the network structure, the self-organization networks in the 5G wireless networks, the neural network used in image recognition, and the optimization problems.

**FRANK YEONG-SUNG LIN** received the B.S. degree in electrical engineering from the Electrical Engineering Department, National Taiwan University, in 1983, and the Ph.D. degree in electrical engineering from the Electrical Engineering Department, University of Southern California (USC), in 1991. After graduating from USC, he joined Telcordia Technologies [formerly Bell Communications Research, (Bellcore)] in Piscataway, NJ, USA., where he was responsible for developing network planning and capacity management algorithms for a wide range of advanced networks. In 1994, he joined the Faculty of the Electronic Engineering Department, National Taiwan University of Science and Technology. Since 1996, he has been with the Faculty of the Information Management Department, National Taiwan University. His research interests include network optimization, network planning, performance evaluation, high-speed networks, wireless communications systems, distributed algorithms, and information security and biometrics.

**YEAN-FU WEN** received the Ph.D. degree from the Department of Information Management, National Taiwan University, in 2007. He is currently an Associate Professor with the Graduate Institute of Information Management, National Taipei University, Taiwan. His research interests include cloud computing, performance optimization, cognitive radio, resource allocation, and cross-layer technology in next-generation wireless networks.